A COMPUTATIONAL TOOL FOR MICROSTRIP PLANAR FILTER DESIGN

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A project report submitted in partial
fulfilment of the requirements for the award of the
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Dedicated to,

My beloved father and mother,

Hashim Mahgoub Elsayed and Muna Hammed Abdurahman

My brother soul,

Ahmed Hashim,

may his soul be embraced in the sacred bond of eternal

life and rest in peace,

My brothers,

Amged and Mohammed,

My siblings,

Molhema, Linda, and Lowrain,

My supervisor Dr. Samsul Haini Bin Dahlan, and My friends.

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Besides my advisor, I would like to thank my family: my Dear parents, my brothers, and my friends for supporting me spiritually throughout writing this thesis and my life in general. For everyone believes “Yes I can” … **YES I COULD**

ABSTRACT

Filters are very important part of any communication system. Naturally, RF and microwave systems belong to these systems. Microwave filters are needed in a wide range of applications including satellite communications and wireless communications as well as military applications. Planar filters among the other types of Microwave filters have the advantages of small size and portability. Moreover, planar filters are very appropriate for very high frequencies.

With the rapid development of the technology in all aspects of our lives and to meet the aggressive project schedule deadlines and quality requirements which are needed by the engineers in the industrial field of planar filters design, the concept of developing software programs to develop planar filters emerges. Another important point, the fact that for both researchers and students it is not that easy to get a well understanding of the microwave concepts as well as its devices from textbooks alone.

Through this thesis, an explanation of a tool known as (FILSoft) will be provided. The tool is developed based on Matlab-GUIs. Furthermore, the tool designs Microstrip line filters with experienced engineers' design quality in a shorter time than by traditional design procedures. FILSoft is a user friendly design tool, the design procedures through this tool start from lumped elements filter up to Microstrip filter. The user just needs to insert the required filter specifications and the design's material description then all the required results will be displayed including lumped element filter along with Microstrip filter structure and the filter frequency response. The tool is able to design both Butterworth and Chebyshev analytical functions along with the four types of filters; Low Pass Filter (LPF), High Pass Filter (HPF), Band Pass Filter (BPF), and Band Stop Filter

(BSF) using two types of Microstrip structure, the first structure is the Stepped Impedance, while the second one is the Parallel Coupled Line. Finally, a LPF is designed by our tool (FILSoft) and then it is simulated by CST studio package and finally is implemented by fabrication, then a comparison is made to investigate the performance and to prove the concept of our tool.

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CHAPTER 1

INTRODUCTION

1.1 Preamble

Today's engineers require software programs to support the accuracy and throughput demands needed to meet aggressive project schedule deadlines and quality. Of course, RF and Microwave engineers are not an exception. Since the filters are one of the most important parts in the Microwave system a lot of software programs have been developed to fulfill today's requirements for filters design. Most of the developed software programs are for circuit level design and the rest are up to physical layout structure.

1.2 Research Background

Engineers and students cannot run away from adapting software programs into their process of studies and designs to support the ever increasing and challenging research, teaching, industrial field designing demand. Of course, RF and Microwave Engineering is not an exception. Here in the Research Center for Applied Electromagnetics (EMCenter) of University Tun Hussein Onn Malaysia (UTHM), the idea of developing our own friendly software package to design Microstrip planar filters was come out for many reasons.

First of all, the fact that for researchers, students, and engineers, it is not that easy to get a well understanding of Microwave concepts as well as its devices from textbooks only. Moreover, the waste of time due to the time which is taken by them to look for the appropriate equations of Microstrip filters basic structures to be the base of more advanced design, since the fact that to design an advanced structure requires starting from the basic structures first. Additionally, the cost-effectiveness of this kind of design's software packages generally is a very important factor. Together with the fact that the available software packages such as CST Studio (CST, 2017) which is 3D Electromagnetic Simulation Software and it is commonly used for the purpose of filter design are commercial and even complicated for the beginners. In other words, the designer should calculate all the design dimensions first and then these software packages come as a second stage, and this consumes time, effort, and of course, the arithmetical errors can happen.

Generally in any communication system, filters can be defined as two-port networks, which are used to control the spectrum and suppress interferences at a certain point. They perform their functionalities by allowing transmission at frequencies within the passband of the filters and on the same time reject the frequencies which are in the stopband of the filter.

In the years preceding World War II, the development of filter theory and practice began by pioneers such as Mason, Sykes, Darlington, Fano, Lawson, and Richards. The image parameter method of filter design was first introduced in the late 1930 and was useful for low-frequency filters in radio and telephony. A group at Stanford Research Institute, consisting of G. Matthaei, L. Young, E. Jones, S. Cohn, and others, started investigating and researching in microwave filter and coupler development in the early 1950. As a result of the work of Stanford Research Insititude group a handbook on filters and couplers was published and remains a valuable reference. After all this years, in today's research industrial community most microwave filter design is based on computer-aided design (CAD) packages using the insertion loss method.

The use of low temperature superconductors and other new materials, and the incorporation of active devices in filter circuits due to continuing advances in network synthesis with distributed elements, microwave filter design remains an active research area. Another reason in the recent years, the usage of computer-aided design (CAD) packages is dynamically grown due to the increment in the demanding for filters with a super accurate dimensions for both research and industrial field.

When Microwave filters designed using the image parameter method, they consist of a cascade of simpler two port filter sections. This method provides the desired cutoff frequencies and attenuation characteristics but on the other hand, it does not allow the specification of a particular frequency response over the complete operating range. It can be concluded, although the procedure is relatively simple, the design of filters by this method often must be repeated many times in order to optimize the results.

Furthermore, a more modern method, called the insertion loss method, uses network synthesis techniques to design Microwave filters with a completely specified frequency response. This method begins with low-pass filter prototypes that are normalized in terms of impedance and frequency. Whenever a different type is required then transformations are applied to convert the prototype designs to the desired type.

Both the image parameter and insertion loss methods of filter design lead to circuits using lumped elements (capacitors and inductors). For microwave applications such designs usually must be modified to employ distributed elements consisting of transmission line sections. The Richards transformation and the Kuroda identities provide this step (Pozar, 2012).

According to (Hong & Lancaster, 2001), Microstrip planar filters have many structures such as; stepped-impedance filters, open-stub filters, semilumped element filters, end- and parallel-coupled half-wavelength resonator filters, hairpin-line filters, interdigital and combline filters, pseudocombline filters, and stub-line filters are widely used in many RF/microwave applications. The stepped-impedance structure and the parallel-coupled line structure are the most common usage and very simple structure to design the low-pass and bandpass Microwave filters. In the case of high-pass and bandstop Microwave filter structures such as quasilumped element and optimum distributed high pass filters, narrow-band and wide-band bandstop filters are used.

1.3 Problem statements

The motivation behind the development of planar filters design software program is to improve filters performance and also to increase the overall efficiency of the design. An efficient design process is required in a competitive commercial environment, especially when orders for filters with different specifications are presented and rapid design and manufacturing is essential.

Additionally, the planar filters designing is a complex process. Coupled with the fact that the exciting designing software programs have been developed for the expert engineers who have a strong background about Microwave's field and there is little explanations provided by the designers.

1.4 Objectives

The objective of the project is to design a friendly interface software program which is able to design and analysis Microwave's planner filters to simplify and accelerate the process of filter designing for inexperienced engineers and students. The purposes of the project can be summarized into three points:

1. To develop a program based on Matlab with a friendly interface to design and analysis Microwave's planar filters.
2. To validate the performance of the developed software using CST studio package.
3. To prototype a LPF as a proof of concept to verify the software's accuracy.

1.5 Scope

The scope of this project is focused on developing a software program which is able to design Microwave's planar filters automatically based on Matlab-GUIs using the insertion loss method. Furthermore, the software program is able to design Butterworth and Chebyshev types of analytical functions and the four types of filters, which are: Low Pass Filter (LPF), High Pass Filter (HPF), Band Pass Filter (BPF), and Band Stop Filter (BSF). Moreover, the software program implements the planar filters by using two types of physical structure techniques. The first technique is the Stepped Impedance, while the second one is the Parallel Coupled Line.

Additionally, in order to investigate the performance of the developed software program, CST studio package is used. In the CST studio the Circuit & Component from the MW & RF & Optical application area panel is chosen and within this application area, the Planar Filter workflow is selected. The results which are taken from the filter designed by CST studio are by using the Time Domain Solver.

Finally, a LPF which is designed as a proof of concept to verify the accuracy of the developed software program is implemented using etching technique and FR-4 as a substrate material. The measurements of the fabricated LPF is done using a Vector Network Analyzer (VNA) in the Center of Applied Electromagnets in UTHM .

1.6 Thesis outline

The thesis contains five chapters, the First Chapter is the introduction which is composed of a preamble, study background, problem statements, objectives, scope, and finally the thesis outlines. Secondly, the literature review, which contains details about the important system concepts, the previous related works, and summary of what have been done before is presented in Chapter 2. The Third Chapter is the research methodology, which contains the algorithm of the system design and the mathematical modeling. Chapter 4 is presented an explanation for the MATLAB GUIs, data analysis and discussion of the results, and a validation to ensure the accuracy of the tool. Finally, in Chapter 5, the conclusion and a group of recommendations for future works as well.

CHAPTER 2

LITERATURE REVIEW

2.1 Preamble

In this chapter several fundamental concepts and definitions pertaining to Microwave filters design will be reviewed. Moreover, a brief comparison between a group of available commercial software program will be provided. Firstly, Microstrip transmission line is discussed. Secondly, Microwave filters design methods are displayed, along with a brief explanation about the concept of the insertion loss method and the structure of two famous Microstrip filters design techniques. Finally, a deep comparison between a group of available software programs to come out with the gap that needs to be full filled.

2.2 Microstrip transmission line

One of the most popular transmission lines is the metallic waveguide to transfer high frequency electromagnetic waves (Pryce, 1946). However, for the frequencies beyond 10 GHz, and due to skin effect, the resistance of the waveguide increases significantly (Forbes & Gorman, 1933). According to (Bryant & Weiss, 1977), the Microstrip line is one of the most common usages for this purpose. It consists of upper and lower metallic layers and between those layers a dielectric substrate. Figure 2.1 represents the schematic of the Microstrip line, while Table 2.1 represents some the nomenclature related to the Microstrip line.

Table 2.1: Nomenclature related to the Microstrip line.

Name	Description
W	Width of the metal conductor
H	Height of the dielectric substrate
ϵ_r	Dielectric constant of the substrate

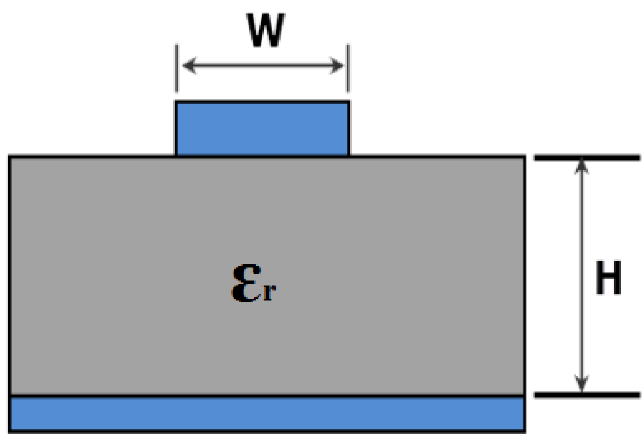


Figure 2.1: Schematic of the Microstrip line.

Microstrip and printed circuit boards (PCBs) both function in the same way at low frequencies. PCBs can be used for low frequencies applications up to a few hundred MHz. However, at microwave frequencies, the losses become so high and this makes their use impractical. On the other hand, when Microstrip is used less loss occurs due to its special dielectric substrate that confines the signal (Niehenke, Pucel, Fellow & Bahl., 2002).

The characteristic impedance of a Microstrip depends on three main parameters, those parameters are; The dielectric constant (ϵ_r), the substrate high (H), and The line width (W). Many researchers such as (Bahl & Grag, 1977), (Owens, 1967), and (Yamashita & Atsuki, 1969) attempt to approximate equations in order to realize

Microstrip circuits. The expression used commonly to realize Microstrip circuits is formulated by Bahl and Trivedi in 1977.

2.3 Microwave filters design

The process of Microwave filter design can be divided into several steps according to (Pozar, 2012), (Hong & Lancaster, 2001), and (Sobol, 1971). Figure 2.2 displays a block diagram describing the general idea of Microwave filter design.

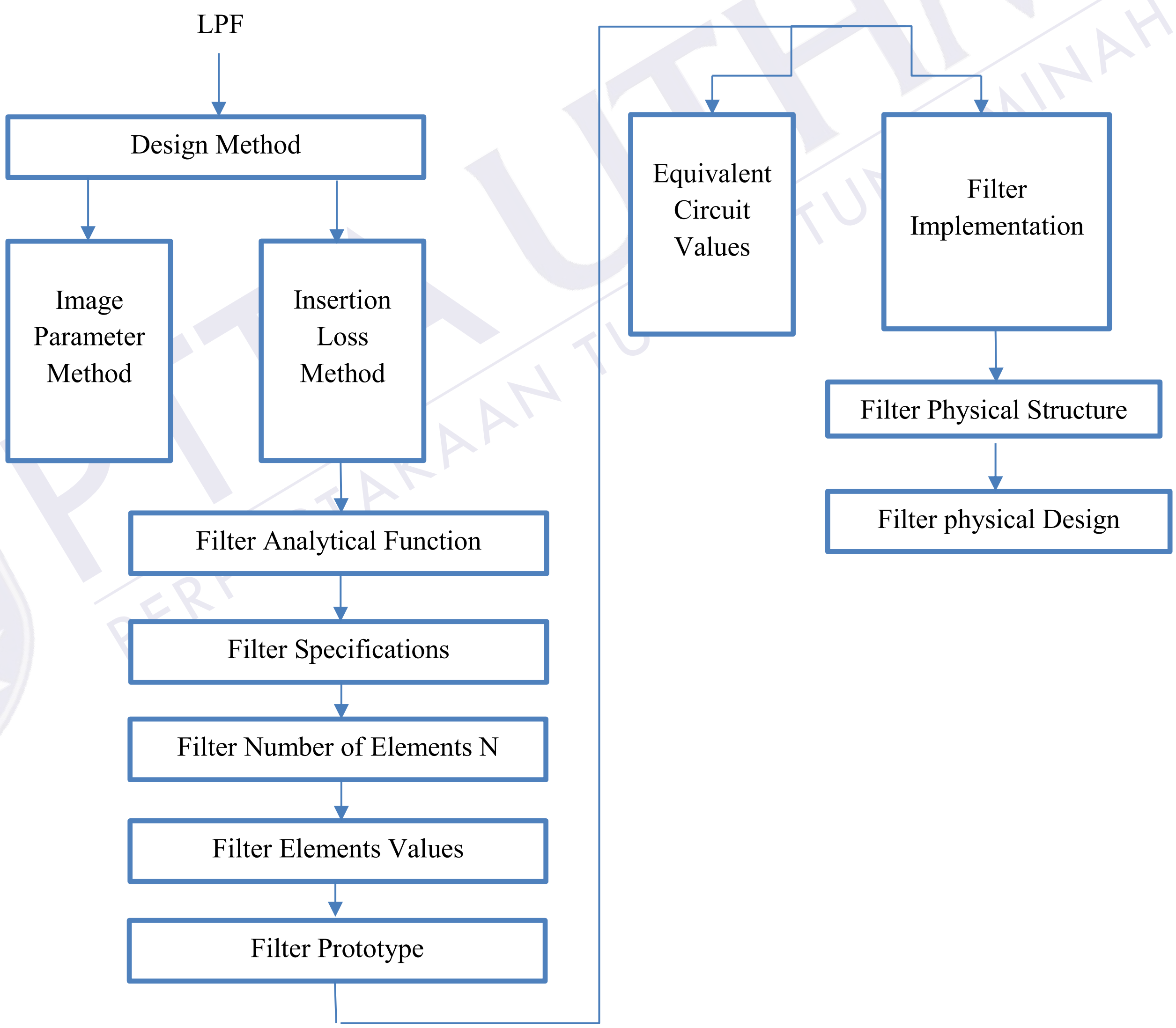


Figure 2.2: Microwave filter design block diagram.

Table 2.2 contains a brief explanation on the functionalities of the blocks in Figure 2.2.

Table 2.2: Blocks functionalities.

Block Name	Function
Filter Analytical Function	• Butterworth. • Chebyshev. • Bassel.
Filter Specifications	• Cut-off frequency. • Center frequency. • Minimum insertion loss. • Bandwidth.
Filter Physical Structure	• Stepped-impedance. • Parallel-coupled line. • Stub.

Generally, there are two methods used to design Microwave filters. The first method is known as the image parameter method, while the second method is called the insertion loss method. For both methods the designing process start from the lowpass filter prototype. In the image parameter method, the specifications of passband and stopband characteristics a cascade of a simple two-port network is involved. Although the image parameter method is simple, but the main problem of this method is that the designer has no full control over the arbitrary frequency response of the designed filter. On other words, the designer will not be able to improve the designed filter mathematically, when the image parameter method is used. The image parameter method is useful when it comes to design simple filters.

On the other hand, the insertion loss method permits the designer to control the passband and stopband amplitude and phase characteristics, with a methodical way to synthesize a required response. The necessary design trade-offs can be evaluated to best meet the application requirements (Pozar, 2012).

2.3.1 Insertion loss method

In (Vilović, Konjuh & Burum, 2009), the insertion loss method allows the filter performance to be improved. The insertion loss method begins with the design of a low-pass filter prototype that is normalized in terms of impedance and cutoff frequency. The normalized design of low-pass filter is then transformed to the filter with desired impedance level, frequency response and cutoff frequency. In this method a filter response is defined by its insertion loss or power loss ratio as it can be seen in Figure 2.3, P_{LR} is represented as follows:

$$\mathrm{P_{LR}} = \frac{P_\mathrm{i}}{P_\mathrm{i} - P_\mathrm{r}} = \frac{1}{1 - \frac{P_\mathrm{r}}{P_\mathrm{i}}} = \frac{1}{1 - \Gamma\Gamma *} = \frac{1}{1 - |\Gamma(\omega)|^2} \tag{2.1}$$

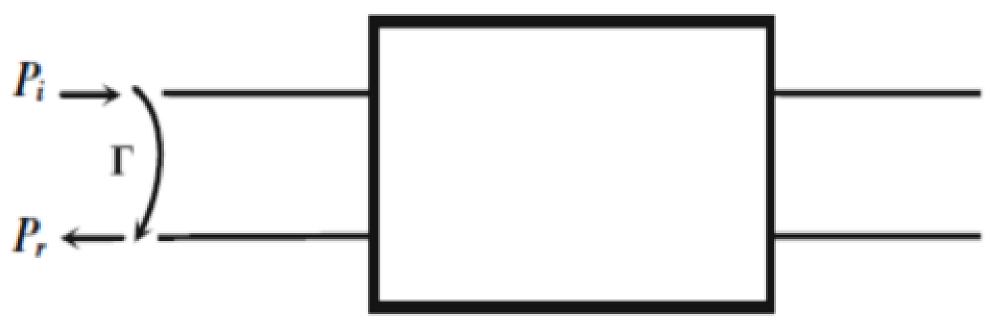


Figure 2.3: Schematic diagram of power loss ratio (Awang, 2014).

Whereas;

- $\Gamma(\omega)$: the reflection coefficient seen looking into the filter. Since the normalized input reflection coefficient is:

$$\Gamma = \frac{Z_\mathrm{in} - 1}{Z_\mathrm{in} + 1} \tag{2.2}$$

The power loss ratio for maximally flat (Butterworth) low-pass filter can be defined by Equation (2.3):

$$P_{LR} = 1 + k^2 \left(\frac{\omega}{\omega_c}\right)^{2N} \tag{2.3}$$

Whereas;-

- k^2: the passband tolerance.
- N: the number of filter elements.

For equal-ripple low-pass filter prototype (Chebyshev filter) power loss ratio can be determined using Equation (2.4):

$$P_{LR} = 1 + k^2 T_N{}^2 \left(\frac{\omega}{\omega_c}\right) \tag{2.4}$$

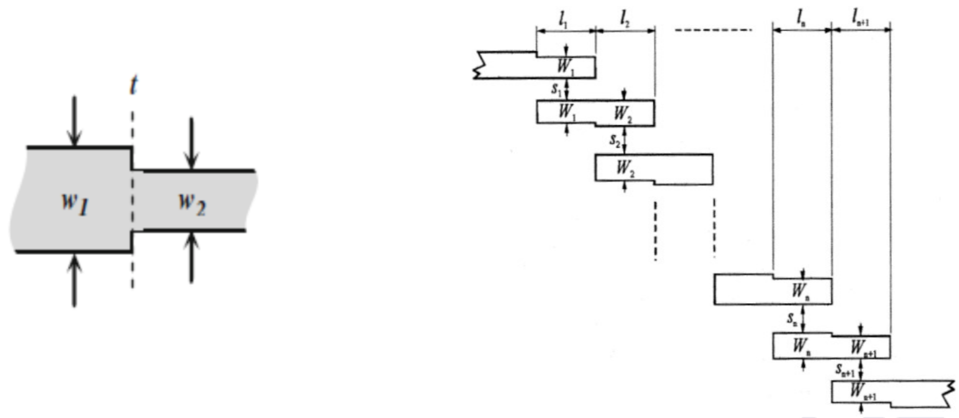
Whereas;

- T_N: is a Chebyshev polynomial of order N.

2.3.2 Microstrip filter physical design

One of the most popular ways to implement microwave low pass filters in Microstrip line is by using a periodic structure of two sections with high and low characteristic impedance, which known as stepped-impedance. This implementing method is the easiest, simplest way to implement Microstrip filters. Furthermore, it takes less space compared with other methods (Pozar, 2012).

In (Hong & Lancaster, 2001) the parallel coupled line is another technique to construct microwave filters in Microstrip lines, which is very effective and easy technique to fabricate band pass and band stop filters with fractional bandwidth less than 20%, for wider bandwidth it is difficult to be fabricated due to wider bandwidth require very tightly coupled line. Figure 2.4 displays some basic structures of Microstrip filters.



(a) (b)

Figure 2.4: Some basic structures of Microstrip filter (a) Stepped-impedance, and (b) parallel-coupled (Hong & Lancaster, 2001).

2.4 CST Studio

CST STUDIO® is a powerful tool for the 3D electromagnetic (EM) simulation of high frequency components. CST Studio offers unparalleled performance, making it first choice in technology leading R&D departments. CST MWS enables the fast and accurate analysis of high frequency (HF). CST is not limited to only Microwave filters, it also supports a wide range of electromagnetic devices such as antennas, couplers, planar and multi-layer structures and SI and EMC effects. Exceptionally user friendly, CST Studio quickly gives an insight into the EM behavior of high frequency designs (Cst, 2017). CST Studio supports five different applications: MW & RF & OPTICAL applications, EDA/ELECTRONICS applications, EMC/EMI application, CHARGED PARTICLE DYNAMICS applications, and STATICS AND LOW FREQUENCY applications. Each of these applications contains several areas. MW & RF & OPTICAL is our choice in this research area. MW & RF & OPTICAL choice contains six areas: Antennas area, circuit & components are, radar cross section area, "biomedical, exposure, SAR" area, optical applications area, and periodic structure area. Each of the previous areas supports many workflows. Figure 2.5 display the MW & RF & OPTICAL with its applications area, while Figure 2.6 shows the circuit & components application area with its workflows.

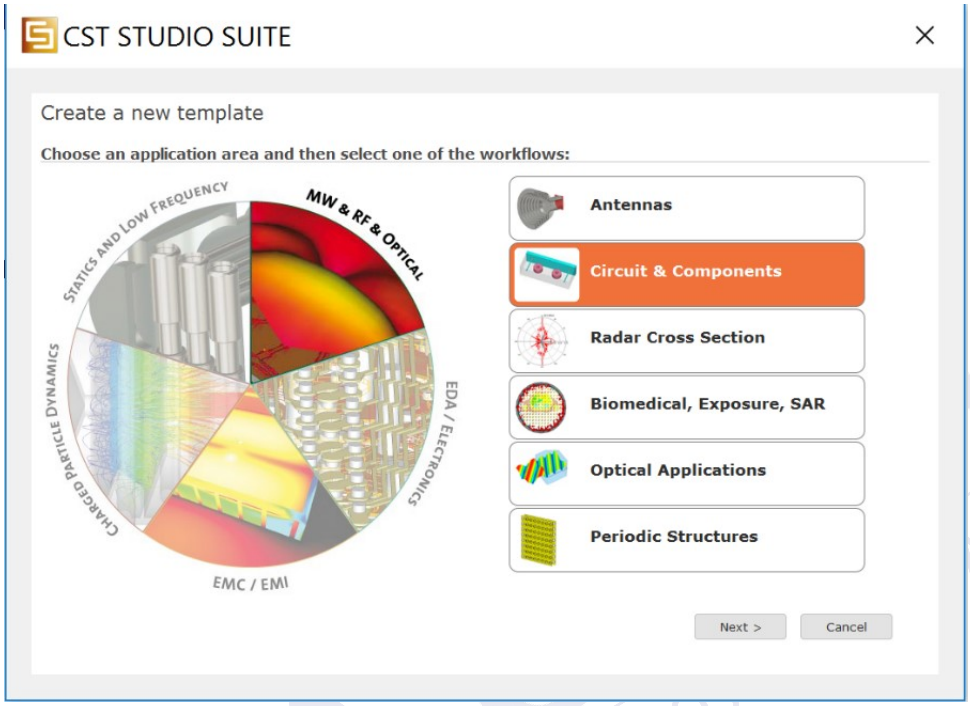


Figure 2.5: MW & RF & OPTICAL with its applications area.

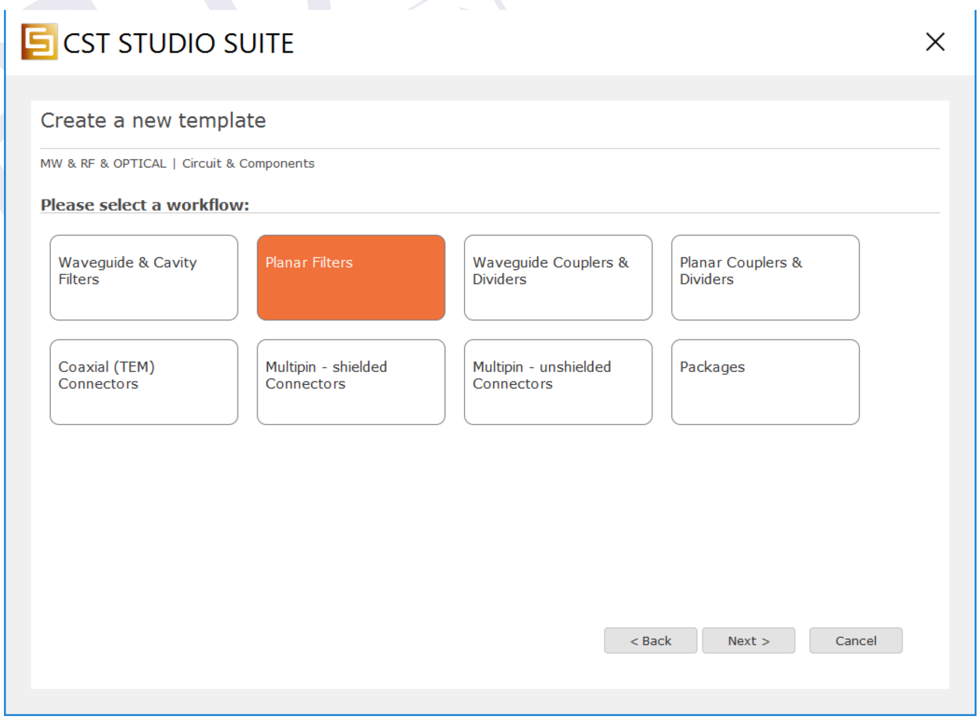


Figure 2.6: Circuit & components application area with its workflows.

2.5 Available software tools for filters design

Software packages are an essential requirement for the design of filters. Their use prevents the costly process of redesigning and rebuilding prototypes and often ensures a final design that gives a close-to-optimal performance. This sections will discuss the capabilities of the available design software packages, including a group of those purchasable from the well-known companies, such as WEBENCH Active Filter Designer, Elsie™, FilterLab® Filter Design Software, and Filter Wiz PRO active filter designer. Furthermore, CST studio package will be discussed to illustrate the different between it and the rest of discussed packages. The discussion will cover many aspects such as the range of operating frequency, the maximum order of the filter that can be designed using this software program, the technique which the software used to design filters, and the final result of each software program.

2.5.1 WEBENCH® active filter designer

According to (Texas Instruments, 2017), WEBENCH® Filter Designer lets the user design, optimize, and simulate complete multi-stage active filter which is used for cutoff frequencies that range from sub 1 Hz to 10 MHz. Create optimized filter designs using a selection of TI operational amplifiers and passive components from TI's vendor partners.

WEBENCH® Filter Designer allows the user to design Lowpass, Highpass, Bandpass, and Bandstop filter types. Specify performance limitations for attenuation, group delay, and step response. Choose from a variety of filter analytical functions such as Chebyshev, Butterworth, Bessel, transitional Gaussian to 6 dB, transitional Gaussian to 12 dB, linear phase 0.05°, and linear phase 0.005°. Find out the filter response best suited for your design by optimizing for pulse response, settling time, lowest cost, passband ripple, and stopband attenuation. Moreover, a superb option to analyze the designed filter by using SPICE electrical simulation with closed-loop frequency response, step response, and sine-wave response analysis options. Figure 2.7 displays the main interface of the WEBENCH® Filter Designer.

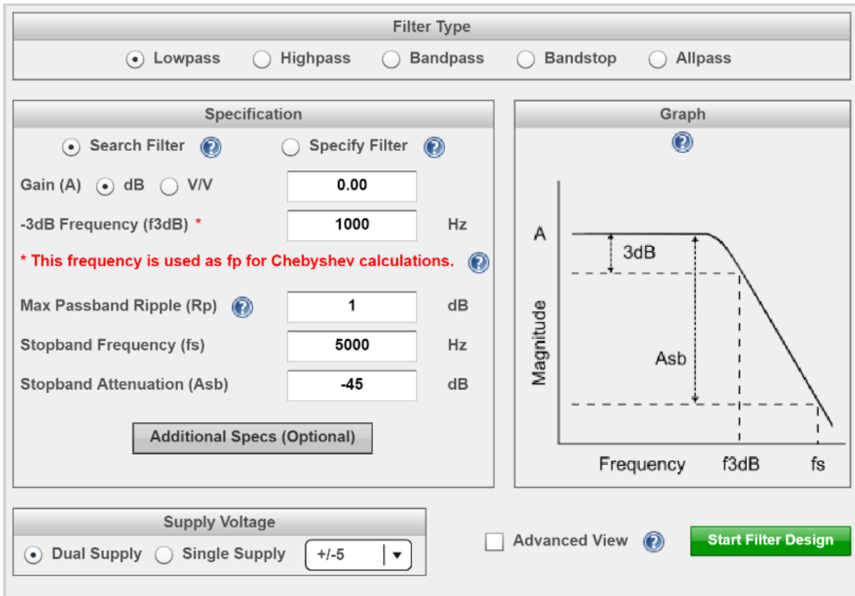


Figure 2.7: WEBENCH® Filter Designer main interface (Texas Instruments, 2017).

2.5.2 Elsie™

Elsie™ is an uncommon commercial-grade lumped-element ("L-C") software program to design and analysis electrical filters. Two versions are available, the first version is the free Student Edition of Elsie, it is quite sufficient to be used by students or small manufacturing operations. The second version is with the key, which performs more capable Professional Edition. The limitation on the number of network components is the key difference between the Student Edition and the Professional Edition of Elsie. In addition, the editing library of manually-entered components is limited in the Student Edition to only inductors, capacitors, and resistors. That means components such as lines, stubs, transformers or coupled inductors are not available. The previous mentioned component and more are available in the Professional Edition. Figure 2.8 shows the main screen of the Elsie™ software (Tonnesoftware, 2017).

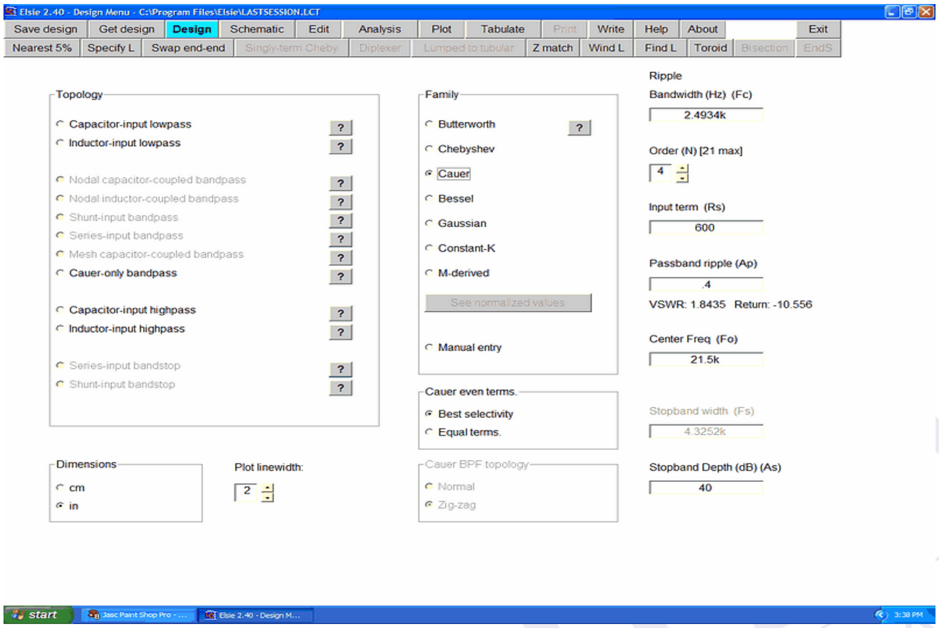


Figure 2.8: Elsie™ software main screen (Tonnesoftware, 2017).

Moreover, the "number of network components" is limited only for 7 for the Student Edition, while in the Professional Edition 41 network components are available. For filter design, the order is limited to 10 only in Bessel and Gaussian, while in the other cases, 7 order are available for the Student Edition and 21 order for the Professional Edition (because the lookup table) (Tonnesoftware, 2017).

2.5.3 FilterLab® filter design software

FilterLab® is an innovative software tool to simplify the process of active filter designing. It is free software and available at (Microchip) website, the FilterLab® active filter software design tool provides full schematic diagrams of the filter circuit with recommended component values along with the frequency response.

FilterLab® active filter software designs low-pass filters up to an 8th order filter with many types of analytical functions such as; Chebyshev, Bessel and Butterworth responses from frequencies of 0.1 Hz to 1 MHz. Moreover, it designs band-pass and high-pass filters, but it is only limited for Chebyshev and Butterworth types of analytical functions. Additionally, Low-pass filters by using either the Sallen Key or Multiple Feedback topologies, while Band-pass filters by using the Multiple Feedback topology, and High-pass filters by using the Sallen Key topology. Finally, capacitor values can be manually selected. Generates a SPICE model of the designed filter. Figure 2.9 presents main FilterLab® design panel (Microchip, 2017).

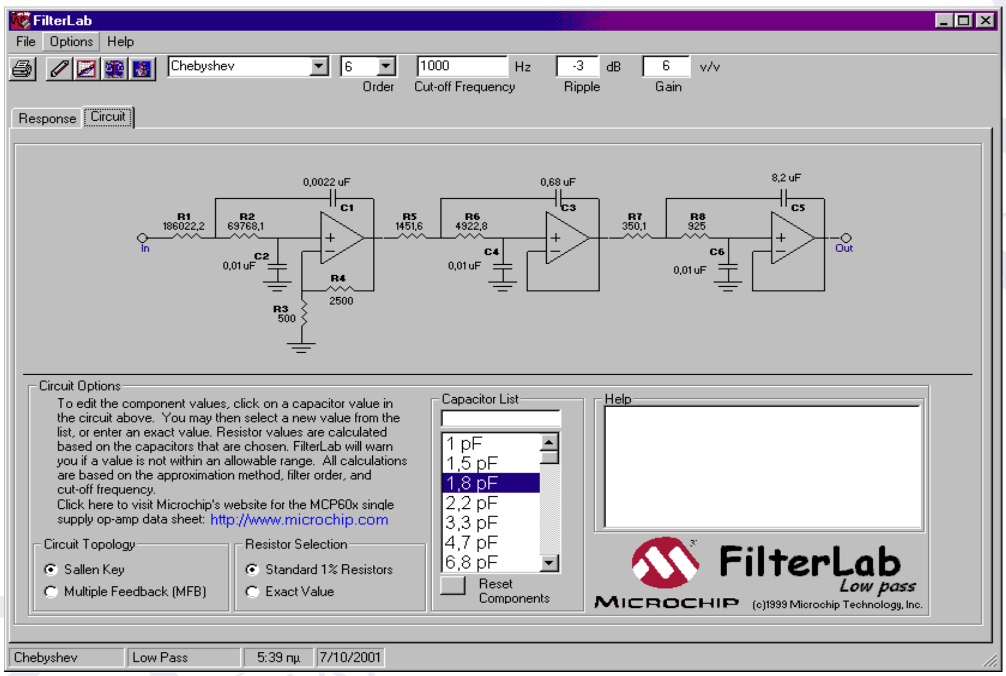


Figure 2.9: Main FilterLab® design panel (Microchip, 2017).

2.5.4 Filter Wiz PRO active filter designer

Filter Wiz PRO offers in-depth design and highly customizable solutions. It offers new anti-aliasing filter design by design an anti-aliasing low pass filter for A/D conversion. Additionally, it allows instant access to all completed phases of the filter design and presents information and choices with clarity and ease of use. Moreover, it allows up to 21 Approximations to be chosen by the user. The user can choose from 10 "standard" Approximations, plus 5 linear phase Approximations, and 6 Low-Q Approximations that are significantly useful for enhancing filter stability. Approximations include;

Butterworth, Chebyshev, Inverse Chebyshev, Elliptic, LSM, Mod. Butterworth, Bessel, Low-Q Butterworth, Low-Q Chebyshev, Low-Q Elliptic, Linear Phase, and Legendre. Furthermore, Filter Wiz PRO offers many circuit topologies which the filter can be implemented using them such as; Sallen-Key, Multiple Feedback, Fliege, Bach, Twin-T, KHN, Tow-Thomas, and Natarajan. It also able to design filters of order 3 to 20 are constructed of simpler first and second order stages cascaded together. Figure 2.10 displays the main screen of Filter Wiz PRO (Schematica, 2017).

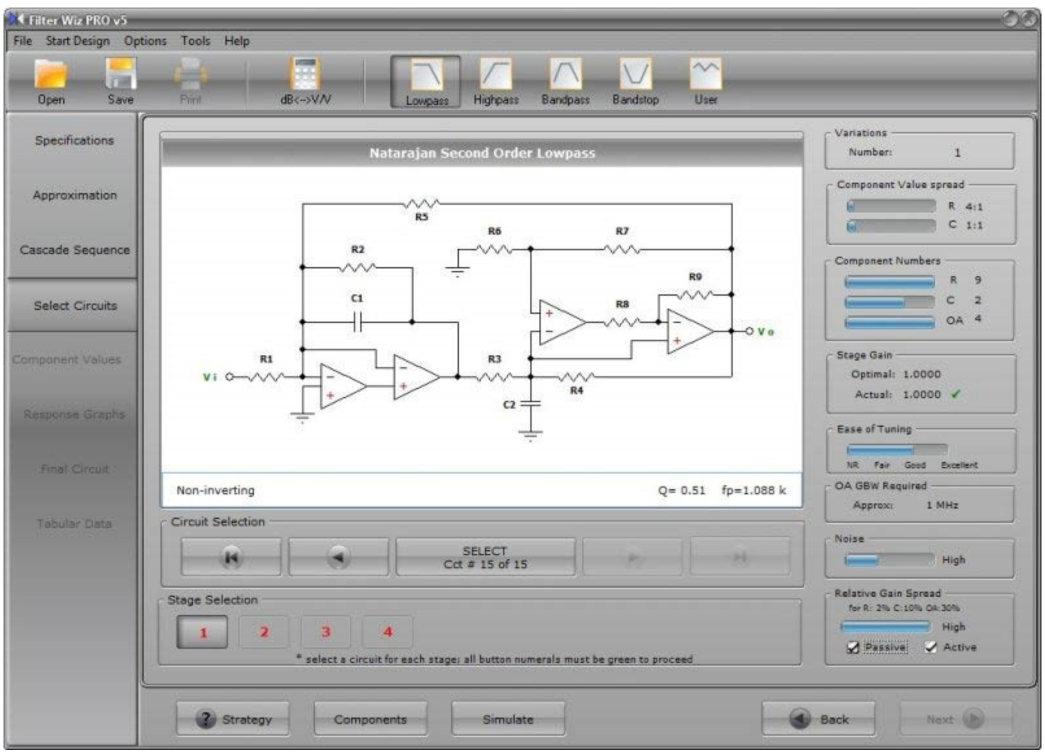


Figure 2.10: Main screen of Filter Wiz PRO (Schematica, 2016).

2.6 Summary

The above discussed software programs can be summarized in Table 2.3. The summarizing is based on five main parameters; the frequency range, the maximum order which the software program is able to design filter with it, the design topology which describe the electrical concepts that the software program design filter based on them, final result which explain the final filter circuit, and the license to show whether the software program is free or commercial.

Table 2.3: Summary of the existing filter design software programs.

Parameter	WEBENCH	FilterLab	Filter Wiz PRO	Elsie
Frequency range	Up to 10 MHz	Up to 1 MHz	Up to 1 MHz	Up to 10 GHz
Maximum order of designed filter	--	8	20	41
Design topology	Operation Amplifier	Operation Amplifier	Operation Amplifier	Lumped Element
Final result	Electrical Circuit	Electrical Circuit	Electrical Circuit	Physical Structure
License	Open	Open	Open	Commercial

From Table 2.3, it can be noted that for the first three software programs which are WEBENCH, FilterLab, and Filter Wiz PRO although they are open license software, but they are limited to low frequencies which are out of Microwave range. On the other hand, Elsie is the only software program among the discussed tools which operates in the Microwave range, but it is a commercial software program.

Another interested point, it can be noted from Figure 2.7 to Figure 2.10 which display the design interface of the above discussed software programs. Those interfaces are quit complicated specially for those who have weak background related to filter design.

It can be concluded that to develop a software program which is able to design filters for the Microwave frequencies and in-house license will be our contribution in this research.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Preamble

This chapter will describe the practical steps that followed by the software program to design Microwave filters. This methodology contains several steps, and each step should be completed before proceeding to the next steps. It consists of the explanation on how the software program starts prototyping an appropriate LPF according to the targeted response and calculates the optimum number of element for both Butterworth and Chebyshev types of analytical functions. Together with an explanation on how to transform the LPF prototype to the other types of filters whenever it is required. Furthermore, the techniques that use to sketch the frequency response of the required filter and the calculation of physical layout will be explained. Figure 3.1 shows the flow chart for the processes that performed by this software program. As it is represented in the flowchart there are three steps which are done by the user of the software manually. The user have to choose the response and the type of the filter and then insert the filter's specification. The rest will be done by the software according to the inserted parameters by the user. To put on other words, the software program calculates automatically up to the optimum physical layout which achieves the required specifications that were inserted by the user of the software program. Moreover, the designing process is based on the insertion loss method, therefore, all the equation and method will explained in this methodology which will but this fact into consideration.

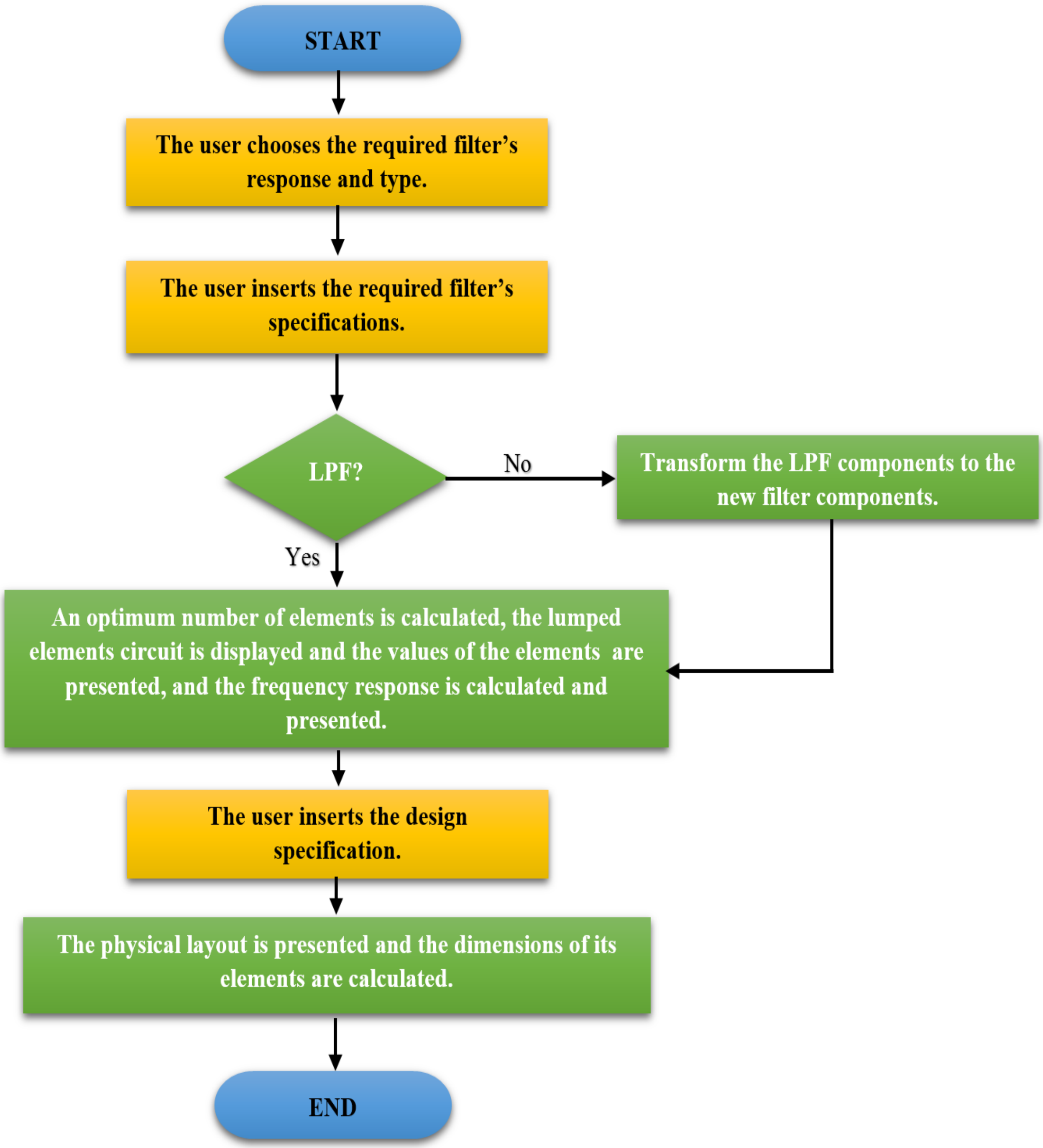


Figure 3.1: The work flow of the software program.

3.2 The filter's elements calculation

As it mentioned in the introduction of this chapter the design is based on the insertion loss technique. Of course, using insertion loss technique means that the whole process starts by the low pass filter prototype, while for the other filters a process of transformation will be applied. The characteristics and the circuit elements of filters can be derived based on the attenuation of the low pass filter, which is basically based on transfer functions, in which the transfer function is specified by the attenuation of the low pass filter. In the attenuation method, a desired attenuation response as a function of frequency (frequency response) is used to approximate the response of an ideal low pass filter.

3.2.1 Maximally flat low pass filter

For the maximally flat low pass filters, the maximum insertion loss α or α_{dB} always occurs at the cutoff frequency. Another word, the cut-off frequency of the maximally flat low pass filters is defined at the point corresponding to the maximum insertion loss. Typically, this point is chosen at -3dB loss. Figure 3.2 displays 3 different responses of maximally flat low pass filter to explain the main point of discerption.

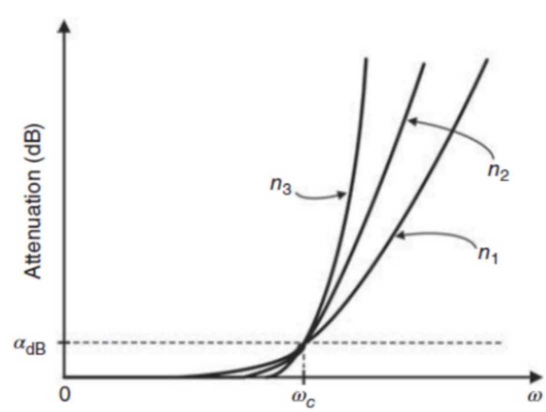


Figure 3.2: Response of the maximally flat low pass filters. $n3 > n2 > n1$.

The attenuation in maximally flat low pass filter which is used to describe the slop of the curve can be defined by the following equation:

$$A_m = 1 + \alpha \left(\frac{\omega}{\omega_c}\right)^{2n} \tag{3.1}$$

Whereas;

- n: the number of low pass filter elements representing the order of the low pass filter.
- ω_c: the cut-off frequency of the low pass filter.
- ω: the frequency at attenuation A_m.
- α: a constant representing the maximum pass-band loss.

In order to calculate the maximum insertion loss for the maximally flat the following equation is used:

$$\alpha = 10^{0.1\alpha_{dB}} - 1 \tag{3.2}$$

3.2.2 Chebyshev low pass filter

The insertion loss constant α is still given by equation (3.2) and α_{dB} is still the maximum insertion loss (in dB), but this maximum loss does not necessarily occur at the cut-off frequency. Equation (3.3) shows that the insertion loss oscillates between the minimum value of 1 (or 0 dB) and maximum value of 1 + α within the pass band, which is due to the nature of the Chebyshev polynomial for $\omega \leq \omega_c$.

The attenuation response of an *n*th order Chebyshev low pass filter is characterized by the following equation:

$$A_c = 1 + \alpha T_n{}^2 \left(\frac{\omega}{\omega_c}\right) \tag{3.3}$$

Whereas;

- T_n: the Chebyshev polynomial of degree n described as

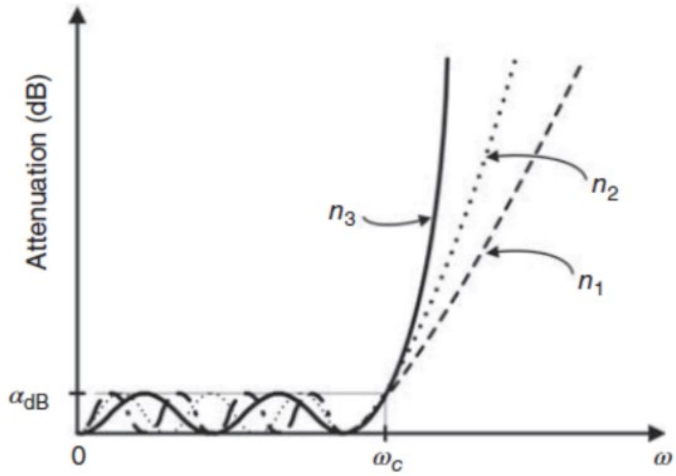


Figure 3.3: Response of the Chebyshev low pass filters. $n3 > n2 > n1$.

$$T_n(x) = \begin{cases} \cos^2\left[n\cos^{-1}\left(\frac{\omega}{\omega_c}\right)\right] & ,\omega \leq \omega_c \\ \cosh^2\left[n\cosh^{-1}\left(\frac{\omega}{\omega_c}\right)\right] & ,\omega \geq \omega_c \end{cases} \quad (3.4)$$

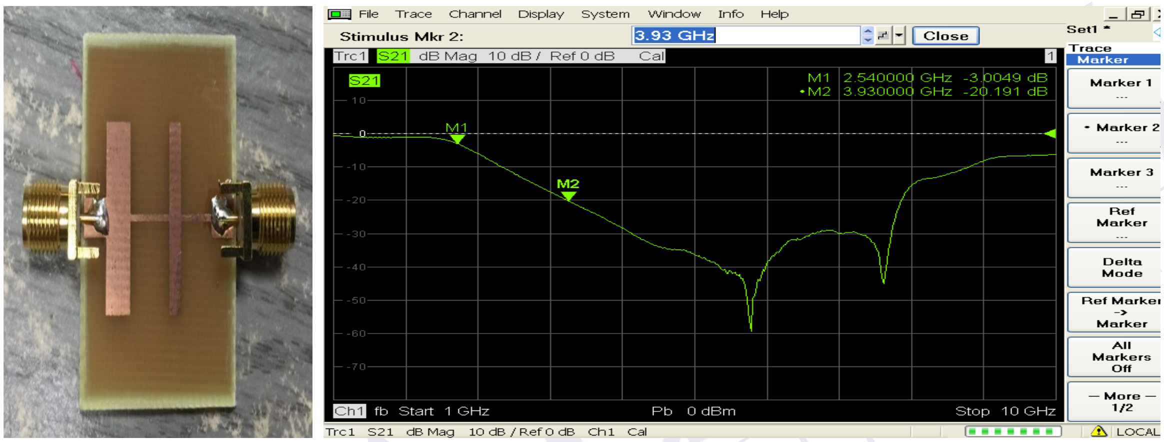
Whereas;

- n: the number of low pass filter elements representing the order of the low pass filter.
- ω_c: the cut-off frequency of the low pass filter.
- ω: the frequency at attenuation A_c.
- α: a constant representing the maximum pass-band loss.

3.2.3 Low pass filter prototype elements

Low pass filter prototypes form the basis for all of the filters including low pass filters, from which these filters are derived, and as such are viewed as the most fundamental filter configurations. In low pass filter prototypes, either end can be used as the source or load impedance due the reciprocity of the passive network. To generalize the results to be obtained for the elements of the low pass filter prototypes from the subsequent formulation, the prototype elements are designated with common variables (g's):

that the filter skirting is much better as it falls steeper compared with the specification. Taking the frequency response in Figure 5 (d) and Figure 8 (b) compared side by side, they are not showing identical results. This is expected as *FILTSoft* calculates the cutoff frequency and the response solely based on mathematical technique, but the prototype bound to its electromagnetic behavior. It takes into consideration the material used, surrounding environment, the current distributions around the circuit, and other electromagnetic parameters which is beyond the scope of *FILTSoft* calculation capability. Hence the measurement result shows significant discrepancies. In overall, *FILTSoft* able to provide a close approximation to optimum filter design and performance according to the specification given, and can be used as an initial guide to prototype the filter.



(a) (b)

FIGURE 8. The fabricated filter (a) filter structure, (b) S_{21} profile.

CONCLUSION

FILTSoft is a computational tool to calculate parameter values of a filter based on mathematical equations. It expedites the process of calculating the physical dimensions of a filter as well as providing user with the expected frequency response. *FILTSoft* provides user with initial idea of how the layout should look like, and how the filter performance is, before they proceed with prototyping the filter. *FILTSoft* cannot simulate and calculate the electromagnetic behavior of the filter. This requires different calculations method and it beyond the scope of *FILTSoft*. However results from *FILTSoft* are very important to give closest guide to achieve the optimum design. By using this tool, it is hoped that the process of learning and designing microstrip planar filters can be made easy.

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